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INTERPRETATION OF CONDUCTOR TEST DATA AND PREDICTION OF REMAINING LIFE

Report No. 90-144-K

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ABSTRACT

ACSR conductors from many of Ontario Hydro's older transmission lines have been tested in the field using a corrosion detector (Cormon). Samples of these conductors have also been tested in the laboratory to determine their tensile strength, torsional ductility and fatigue strength. The Cormon test results show that the average time to virtually complete loss of galvanizing is about 65 years. The tension tests indicate that the average life until conductors fail to support estimated weather dependent static loadings is about 80 years. Resistance to dynamic loads during galloping is measured through fatigue tests of aged conductors. A relationship between torsional ductility measurements and fatigue life has been proposed. An average torsional ductility of the outer layer of steel core wires of about five turns appears to be the practical end of useful life. The test data show that this level is reached on average after about 70 years. Average conductor longevity is highest in the combined Northeastern and Northwestern Regions. Eastern, Western and Central Regions, respectively, have progressively shorter conductors lives. The average life of conductors with single layer steel cores is about 12 years shorter than that of conductors with two layer steel cores. It is concluded that the corrosion detector serves as a useful indicator of impending end of life, while the torsional ductility tests are a more precise guide for scheduling conductor replacement. Further work is required to: verify the torsional ductility-fatigue life relationship; complete the survey of the condition of older lines; and assess the value of more corrosion resistant conductor cores.

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EXECUTIVE SUMMARY

INTERPRETATION OF CONDUCTOR TEST DATA AND PREDICTION OF REMAINING LIFE

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Tests of ACSR conductors from many of Ontario Hydro's older transmission lines have been carried out in the field using a non-destructive corrosion detector (Cormon). Samples of these conductors have also been tested in the laboratory to determine their tensile strength, torsional ductility and fatigue strength. The Cormon corrosion detector measures the loss of galvanizing from the steel cores of the ACSR conductors. The results show that the average time to virtually complete loss of galvanizing is about 65 years, with considerable scatter attributed to local variations in corrosivity of the air. Due to the increasing acidity in the atmosphere since 1950, the lives of untested younger conductors are expected to be shorter.

As the galvanizing is removed, corrosion of the steel core accelerates and mechanical properties deteriorate. The end of useful life depends on the conductor's ability to withstand the static and dynamic loadings imposed in service by heavy icing, high winds, aeolian vibration and galloping events. The tension tests indicate that the average life until conductors fail to support estimated weather dependent static loadings is about 80 years.

Resistance to dynamic loads during galloping is measured through fatigue tests of aged conductors. A relationship between torsional ductility measurements and fatigue life has been proposed. If confirmed this would permit relatively simple torsional ductility tests to be used to estimate remaining fatigue life. An average torsional ductility of the outer layer of steel core wires of about five turns appears to be the practical end point to resist any significant galloping event. The data show that this level is reached on average after about 70 years.

Cormon, tensile and ductility test data indicate that the geographic location is also a factor in conductor degradation. On average, conductor longevity is the highest in the combined Northeastern and Northwestern Regions. Eastern, Western and Central Regions have progressively shorter conductors lives. A similar analysis of conductors with single layer steel cores shows that their average life is shorter than conductors with two layer steel cores by about 12 years.

It is concluded that the corrosion detector serves as a useful indicator of impending end of life, while the torsional ductility tests serve as a more precise condition indicator and can provide a guide for scheduling conductor replacement. The region and the steel core construction could also enter into the decision making process for the refurbishment of the older lines.

Further work is required to verify the relationship between torsional ductility and fatigue life. The surveys of the condition of older lines should be completed. The use of more corrosion resistant cores, such as aluminum clad steel, should be investigated.

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To Mr. D.E. Horrocks
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INTERPRETATION OF CONDUCTOR TEST DATA AND PREDICTION OF REMAINING LIFE

INTRODUCTION

Within the definition phase of the overhead transmission line refurbishment study[1,2], the condition of conductors has become the focus of the selection of lines for prioritization for actual refurbishment. Surveys and field tests have shown that all other components of the lines; foundations, towers, hardware, and insulators, are generally in good condition. Also, where there has been some local deterioration, these components can be replaced within normal maintenance activities. Overhead ground wires are already the subject of a continuing systematic program of testing and replacement. This report provides an overview of the tests done on conductors, and includes statistical and engineering interpretations of the results, which can be used to guide the overall refurbishment program.

The conductors used on Ontario Hydro's lines built before 1950 are mainly aluminum stranded with a galvanized steel core (ACSR). There are a few old copper conductors in place and samples brought to the laboratory for mechanical tensile strength and torsional ductility tests have shown them to be substantially as new[3]. On the other hand the old ACSR conductors show great variability in their condition[3]. This has been attributed to differences in exposure to corrosive agents, particularly to industrial effluent. Also some of these older conductors have been tested for fatigue strength[4]. There is a separate program of gathering existing data on air quality, and of monitoring it to track progressive changes[5,6]. The past records indicate a progressive increase in acidity over the lives of these lines. It is expected that younger conductors will have shorter lives than the samples discussed in this report due to this increasing aggressivity of the atmospheric corrosion.

Early in this program, it was discovered that the CEGB in England had developed a non-destructive diagnostic tool for detecting loss of zinc from the galvanized steel cores of unenergized overhead lines[7]. This device has been made into a practical tool by Cormon Ltd in England. N-Tech Technologies Ltd of Calgary has the license for applying it in Canada and they have carried out the surveys on Ontario Hydro's lines. The device consists of a coil surrounding the conductor which passes eddy currents through the conductor section. From the in-phase and out-of-phase signals the amount of zinc remaining on the steel core wires can be estimated. The device is packaged with a tug to pull it along a span, a radio transmitter, and a ground station to pick up and store the eddy current signals as the probe traverses the span. This device was calibrated for use on Ontario Hydro's conductor sizes and for pre-selected levels of zinc loss. Recently, it has been modified for use on larger conductors and under live line conditions[8]. Field work had been limited by the difficulty in obtaining outages to

deenergize lines for its use. This has been particularly acute in Central and Western Regions which have most of the pre 1950 lines on the province. Nonetheless, to date, 77 line sections across the province have been tested with the Cormon device and ranked according to zinc loss.

A data base of these conductor test data and other related information, such as weather conditions and atmospheric chemistry data, has been established in support of the continuation of the refurbishment activity. It is anticipated that there will be a continuing need for up to date information on line and particularly conductor condition, and of the changing factors influencing the remaining life. This will be needed to provide data for the continuing prioritization of lines for refurbishment within a manageable program. The results presented in this report are all taken from this data base.

INTERPRETATION OF FIELD DATA

Cormon Rating Versus Age

The data base on corrosion testing of 77 conductors within this refurbishment program is summarized by Table 1. This table shows the circuit and line section tested, the region, the conductor size, construction and age, and the corrosion monitor rating. This is on a scale of 1 to 4 which represents 0 to 20, 20 to 50, 50 to 80 and 80 to 100 per cent zinc loss respectively. The table also includes an estimate of the age at which each conductor is expected to reach a rating of 4. Careful examination of the records suggests a trend to shorter line life in Western and Central, compared to the other regions. This is in agreement with the limited data available on the distribution of SO_2 in the air[5,6], and with the increasing distance from the heavy industrial areas south west of the province modified by local sources within the province.

The data are also summarized in Figure 1 in the form of a graph of Cormon rating versus age of sample. This graph includes a curve representing the main trend of the data, and curves representing 10, 30, 70 and 90 percentiles of the data. The curves are single term power law curves. The mean line is given by:

$$Y = 0.00049\ X^{2.17}$$

where Y is the Cormon rating and X is the conductor age in years. This mean curve indicates an average age to reach a Cormon rating of 4 is 63 years, with the lower decile being 43 years. This curve also permits the remaining life to reach the Cormon rating of 4 to be estimated for each sample. For samples that have lower than average ratings the increase in rating is assumed to follow the trend of the average. For example, if the rating falls at the 75 percentile of the spread of the data, it is assumed to remain at that percentile until it reaches the Cormon rating of 4. The 10, 30, 50, 70 and 90 percentile lines facilitate estimation of the end of life for each sample. These "life" estimates are included in Table 1.

Tensile Strength Versus Age

The data on tensile strength of aged conductors based on laboratory tests of 41 samples[3], from this refurbishment program and from ongoing tests for line maintenance, are summarized in Table 2. This table includes the same descriptive data for each conductor sample as Table 1, the tensile strength data and estimates of life to 80 percent rated tensile strength (RTS) based on these tensile tests. The tensile test results show that there is a trend towards shorter life in the Central and Western Regions, compared with the other regions, confirming the trend of the

Cormon data. Figure 2 shows the data plotted against age, with a mean fitted curve and the 10, 30, 70 and 90 percentile curves. The 10 and 90 percentile curves contain 80 per cent of the results. The mean curve is an exponential function given by:

$$Y = e^{(1.41+0.024\ X)}$$

where Y represents strength loss in percent of initial strength and X is the age in years. It should be noted that the initial strength is estimated to be 112% RTS. Analysis of the test results showed that unreliable predictions result if based on the rated tensile strength, and that the average strength of the conductors when new must have been about 112% of RTS. A critical value of strength loss is needed to permit an end of life to be assigned to each conductor. Based on a design study, considering heavy icing and high wind loading, this is taken to be a reduction of strength to 80 percent of rated strength. Analysis of some existing line sections indicated that an even lower remaining strength would be sufficient to withstand 50 year return period heavy ice loads in many cases. However at 80 percent of RTS of the complete conductor, the steel core has lost approximately half of its original tensile strength and little, if any, ductility remains. This end point is shown in Figure 2. On this basis, the average life to reach the critical tensile strength is 81 years and the lower decile value is 44 years. The curves can be used to give an indication of remaining life, as for the Cormon data. The table includes these estimates for each sample tested. However the loss of torsional ductility is expected to be more critical for most, if not all, line sections.

Torsional Ductility Versus Age

Table 3 shows the test data from torsional ductility tests of 38 conductor samples. It includes the average torsional ductility of the outer layer of the steel core, and a life expectancy for each based on a final torsional ductility of five turns. This criterion has been deduced from the fatigue damage estimated to take place during a galloping event. Fatigue damage may also occur due to aeolian vibration, with many more cycles occuring at lower strain amplitudes. However, no appropriate field data were available. The prediction of end of life based on galloping may introduce some conservatism. This is believed to affect some lack of conservatism due to the samples tested not necessarily being the most degraded sections of conductor. The prediction of fatigue strength based on torsional ductility strain, is described in Appendix 1. Once again there is a trend towards longer conductor life with distance from the south west tip of Ontario.

The ductility data are plotted in Figure 3 against age of the sample. The trend of the results is indicated by the mean curve, and the 10, 30 70 and 90 percentile curves enclose 80 percent of the data. The average age at the critical torsional ductility of five turns is 71 years and the lower decile is 39 years. The curve is an exponential function given by:

$$Y = 40 - e^{(1.65+0.027\ X)}$$

As for the Cormon and tensile strength data, these curves can be used to estimate the total life for each sample. The estimated values of age at a ductility of 5 turns are included in Table 3.

Cormon as a Predictive Tool

The above analysis of the conductor test data indicates a consistent trend of life versus location for the three test methods. This supports the concept that they are measures of related degradation mechanisms. The most critical end of life measure is the ductility as a measure of

ability to resist fatigue during galloping. With the critical levels selected, the Cormon test indicates that total loss of core galvanizing happens several years before ductility and tensile strength indicators reach serious levels. Thus the Cormon test is a very useful diagnostic tool. It can be the key to a systematic and manageable procedure for establishing existing conductor condition, prioritizing conductors for further sampling and, based on the more precise torsional ductility tests, for replacement. This procedure parallels that already in place for the overhead ground wire replacement program.

The life of ACSR conductors is somewhat more difficult to predict accurately than that of galvanized steel overhead ground wires. In most cases the aluminum wires show little loss of strength except where physical damage has occurred due to gun shots, arcing, etc. The in service loads that will result in failure are either heavy ice or galloping loads which are very statistical in nature. However if these lines were left to deteriorate further, more lines would be potentially threatened such that widespread damage would result when threshold level ice and wind storms occur. Perhaps the most noteworthy aspect of each indicator is the slope of the deterioration curve in the vicinity of the critical value. While there is a fairly large scatter in the data, the steep slope indicates rapid conductor deterioration once the core galvanizing has gone.

Conductor Life Versus Region and Conductor Construction

Table 4 shows the results of the three tests on conductors sorted by regions and by the number of layers of steel strands. The regional dependency of the data, including the 90% confidence bounds, is plotted in Figure 4. It is seen that in general, with some variations possibly attributable to local industrial atmospheric effluent, the average expected life of conductors increases with distance from the southwest corner of the province. The average life, as indicated by the average of the three indicators, is about 67 years in Central (including the previous Georgian Bay) Region, 72 years in Western Region, 77 years in Eastern Region and 76 years in the combined Northeastern and Northwestern Regions. The observations made previously regarding the predictive capability of each test, i.e., Cormon results as the first indicator of aging followed by ductility and tensile test results, are consistently observed in each region. Table 4 indicates that total loss of galvanizing could occur when the conductors are about 60, 63 or 70 years old, depending on the location of the conductor. Unacceptable ductility and tensile strength limits are reached between 3 and 8 years and between 5 and 15 years later, respectively.

Conductor construction is included in the descriptions of the samples in Tables 1, 2 and 3. This was investigated to determine whether conductors with two layer steel cores lasted longer than those with single layer cores. Most of the conductor cores investigated had two layers, that is six outer wires plus a king wire. The results of this type of categorization are also listed in Table 4 and plotted, with 90% confidence bounds, in Figure 5. The predicted lifetimes, according to the average of three test methods, showed that the two layer cores had a longer average life, 75 years, compared to the single layer cores, 63 years. Note that for 1-layer conductors, the results indicate that the average expected life based on ductility and tensile strength criteria are almost the same. These findings may also support the use of more corrosion resistant core wires for future conductors.

CONCLUSIONS

1. The studies of the condition of the pre 1950 conductors have confirmed that the galvanized steel cores are corroding.

2. Measurements of galvanizing loss using the Cormon corrosion detector provide advanced warning of severe loss of mechanical properties.

3. Torsional ductility testing of samples cut from the conductors provides a more precise measure of the remaining useful life.

4. A manageable program of conductor inspection and remaining life estimation can be developed based on the Cormon and torsional ductility tests and provide a systematic process for making full use of conductor life with minimum risk of premature failure.

5. Due to the increasing level of atmospheric corrosion, newer conductors are not expected to last as long as these older conductors.

6. The longest conductor lives are found in Northeastern and Northwestern Regions, with shorter lives, in order, in Eastern, Western and Central Regions.

7. Conductors with single layer steel cores last about 12 years less than those with two layer cores.

RECOMMENDATIONS

1. The program of inspection and evaluation of conductors should be continued and extended to all line sections in the Province.

2. Based on the techniques described in this report, the program to determine remaining life of all line sections should be completed and a map of the province showing life expectation in different locations should be compiled.

   This should be based on the following procedure after completion of all mechanical tests:

   a) Assess the weather data for each line scheduled for refurbishment.

   b) Determine the actual design loads and relate these to the remaining tensile strength. Determine the mechanical performance in terms of ice and wind loading and aeolian vibration limiting conditions.

   c) Assess the predicted galloping performance and historic data of the line.

   d) Estimate the fatigue life of the conductor core wires from the ductility data.

   e) Recommend whether to replace the conductor and the time frame required.

3. The program of fatigue tests on older conductors should be completed to calibrate and provide stronger support for the use of torsional ductility to predict fatigue life.

4. The data base of line data, conductor condition and factors defining the corrosivity of each line section should be maintained, and used to record remaining life estimates.

5. Methods of extending the life of conductors, such as greasing the core or use of corrosion resistant steels, should be evaluated.

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APPENDIX 1

Example Estimate of Remaining Life

Ductility Tests and Fatigue Strength

The tests of torsional ductility of the steel core wires are conducted using standardized wire specimens under controlled conditions. A sample of wire is clamped between the two chuck jaws such that the length tested is 120 times the diameter. A tension of about 1 per cent of RTS is applied to the specimen to keep it straight. The jaws are rotated about the specimen axis applying a twist throughout the length of the wire. One full turn applies an average shear strain of 2.62 per cent to the specimen. A typical new galvanized steel wire would undergo about 35 turns prior to failure. This corresponds to a torsional strain, e_t, of 92 per cent. This compares well with the strain at failure in uniaxial tension tests on mild steel which is around 90 per cent[9].

The fatigue strength of steel, in terms of total strain amplitude versus cycles to failure, can be estimated from a single torsion test result. As illustrated by Figure 6, the total strain range, ie twice the amplitude, is the sum of the elastic and plastic strain ranges. The elastic strain can be expressed in terms of the applied stress using Hooke's Law. The plastic strain is related to the applied stress through the cyclic strain hardening curve which is a power law. From measurements on mild steel specimens[9], there is a data base which permits reasonable estimates of these relationships to be made. These can then be used to create the fatigue strength curve for steel core wires based on the ductility test, representing a fatigue test of one quarter cycle.

The total strain, e_t, can be expressed as:

$$e_t = e_e + e_p = s/E + As^n$$

The plastic strain range can be expressed as:

$$2e_p = 0.166 \times (2s/50)^n$$

where the stress range, 2s, is in ksi units. Using the value of 3.23 for the exponent n, from earlier fatigue tests on mild steel[9], enables the value of A to be calculated:

$$A = 0.083 \times .04^{3.23} = 2.53 \times 10^{-6}$$

The stress can now be determined from the plastic strain in the torsional ductility test, e_{po}, which is approximately equal to the total strain, e_{to}:

$$s = (e_{to}/A)^{1/n}$$

The Basquin curve[10], with an exponent, b, of -0.14, taken from the earlier studies[9], relates elastic strain, e_e, to fatigue cycles, n_f, and elastic strain in the torsional ductility test, e_{eo}:

$$e_e = e_{eo} \cdot (n_f/0.25)^b = s/E \cdot (n_f/0.25)^b$$

The Coffin-Manson curve[11,12], with an exponent, c, of -0.52, from the earlier studies[9], relates plastic strain, e_p, to fatigue cycles, n_f, and plastic strain in the torsional ductility test, e_p.

$$e_p = e_{po} \cdot (n_f/0.25)^c$$

Recognizing that the maximum strain in the torsional ductility test is almost all plastic deformation and that the elastic component can be neglected, the fatigue strength is then the sum of the two curves:

$$e_t = e_{to} \cdot (n_f/0.25)^c + (e_{to}/A)^{1/n}/E \cdot (n_f/0.25)^b$$

These curves are plotted in Figure 7 for initial strain values of 92 percent, 26 percent and 13 percent, corresponding to torsional ductility values of 35, 10 and 5 turns respectively. The figure also includes two measurements taken on samples from conductors that have been in service at a location near Oakville since 1911. The torsional ductility tests[13] gave an average number of turns in the outer core wires of 2 with individual wires varying between 1.5 and 2.5. The strain values corresponding to the average ductility is plotted on Figure 7 at a life of 0.25 cycles. This conductor sample was also tested in fatigue using the methods described earlier[4]. At a strain amplitude varying between 0.020 and 0.032 percent, the specimen lasted for 4 million cycles before failure. This point is also included in Figure 7 and it can be seen that the experimental values, while not exactly confirming the predicted curve, do support the trend of the fatigue curve constructed from the ductility measurements. Further test data are needed to calibrate the fatigue predictions more precisely.

Galloping Data and Conductor Strain at the Clamp

The field data on conductor galloping on single conductors are compiled in the form of peak to peak amplitude as a ratio of the sag versus percent of observations in Figure 8. This shows that for about 90 percent of the events the peak to peak galloping amplitude was between zero and equal to the sag. In the remaining 10 percent, amplitudes above the sag were recorded, the maximum being 1.5 times the sag. The extreme values plot used allows the data to be extrapolated to less frequent events and serves to characterize the overall galloping phenomenon for the general case. The number of cycles in a four hour galloping event is estimated to be about 30,000 based on a frequency of 0.5 Hertz.

The strain at a suspension clamp due to galloping can be estimated using the equation for deflections of a conductor under tension at a clamp developed by Poffenberger and Swart[14], and adapted into several useful alternative forms in[15]. The strain, e_c, at the clamp is given by:

$$e_c = 3.142 \; d \; \mathrm{sqr}(m/EI) \; f \; y_{max}$$

where d is the strand diameter, m = mass per unit length of conductor, EI = effective stiffness of the conductor section, f = oscillation frequency, and y_{max} = galloping amplitude. The frequency of oscillation, in one loop galloping is given by:

$$f = \mathrm{sqr}(T/m) \; / \; 2 \; L$$

where t is the conductor tension. The peak to peak galloping amplitude is available as a ratio, k, of the sag, which is given by:

$$y_{max} = k \; s = k \; m \; g \; L^2 \; / \; 16 \; T$$

The strain at the clamp is then given by:

$$e_c = \frac{3.142\ d\ k\ m\ g\ L}{32\ \mathrm{sqr}(T\ E\ I)}$$

The field data from 42 observations of galloping on single conductor lines are plotted in Figure 8. The best fit straight line through the data, which is used to predict the number of strain cycles at each level, gives the following distribution.

Galloping Amplitude Versus Percent of Observations

Galloping Amp/Sag	0.0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5
Percent obs'ns	17	11	12	12	10
Galloping Amp/Sag	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0
Percent obs'ns	9.2	7.3	4.5	4.2	3.3
Galloping Amp/Sag	1.0-1.1	1.1-1.2	1.2-1.3	1.3-1.4	1.4-1.5
Percent obs'ns	2.3	1.7	1.3	0.9	0.6
Galloping Amp/Sag	1.5-1.6	1.6-1.7	1.7-1.8	1.8-1.9	1.9-2.0
Percent obs'ns	0.5	0.32	0.23	0.20	0.12

These galloping amplitudes have been used to calculate the distribution of strains at the suspension clamp of a sample span. The example taken is for a 300 foot span of 336.4 kcmil ACSR conductor, tensioned at 3000 pounds. The conductor diameter, weight, and stiffness (EI), are respectively; 0.721 inch, 0.463 lb./ft, and 2773 lb. in^2. Based on a frequency of galloping of 1/2 Hertz, the number of cycles at each strain level during a four hour galloping event have also been calculated and are included in Figure 7 and the following table. The fatigue life of a conductor that has a low torsional ductility, 5 turns, and proportional reduction of fatigue life by the applied cycles, are also included in the table.

Distribution of Strain at the Suspension Clamp Versus Number of Cycles
in a Four Hour Galloping Event and Calculation of Fatigue Life Using Miner's Rule

Strain percent	0.006	0.013	0.020	0.027	0.034
No. of cycles(N)	5100	3300	3600	3600	3000
Fatigue Life(N_f)	3.3×10^{10}	1.6×10^{8}	1.0×10^{7}	1.9×10^{6}	600000
N/N_f	1.5×10^{-7}	2.1×10^{-5}	3.5×10^{-4}	1.9×10^{-3}	0.0050
Strain percent	0.040	0.047	0.054	0.061	0.068
No. of cycles	2760	2190	1350	1260	990
Fatigue Life(N_f)	280000	140000	84000	53000	37000
N/N_f	0.0097	0.0152	0.016	0.024	0.027
Strain percent	0.075	0.081	0.088	0.095	0.102
No. of cycles	690	510	390	270	240
Fatigue Life(N_f)	26000	20000	16000	12000	10000
N/N_f	0.026	0.025	0.025	0.022	0.024
Strain percent	0.109	0.115	0.122	0.129	0.136
No. of cycles	150	96	69	60	42
Fatigue Life(N_f)	8300	7100	6000	5100	4400
N/N_f	0.018	0.014	0.011	0.012	0.009

The fatigue life of the conductor can now be estimated using Miner's Rule[16], which is widely used for such calculations. The fatigue curves for materials are generated by a series of tests of specimens at constant levels of loading until rupture. For applications with varying loading level each cycle of loading is postulated to reduce the remaining life in proportion to the life at that level of loading. Thus the fatigue life can be estimated for a varying load history. For the above example, considering the highest level of strain, 0.136 percent, the fatigue life is 4400 cycles and the four hour galloping event applies 42 cycles. The amount of life reduction by those cycles is 42/4400 or 0.009. Similarly, the amount of life reduction for each load level has been calculated. The sum of all these life reductions gives the total fatigue life reduction, a value of 1 representing failure. For this example, based on a 5 turn ductility test, the life reduction is 0.285. This means that the conductor would have failed after 1/0.285 of the four hour galloping event, or at 14 hours. For other ductility levels the corresponding estimates of life during a galloping event and the relative life are given in the following table.

Estimated Life of Conductor Under
Galloping Conditions versus Steel Core Wire Ductility

Ductility (turns)	5	10	15	20	25	30	35
Fatigue Life (hours)	14	56	127	225	352	508	691
Relative Life	1	4	9	16	25	36	49

Based on the absolute life predictions, a threshold ductility value of about five turns is a possible guideline for conductor replacement.

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TABLE 1

TESTS OF 77 CONDUCTORS USING THE "CORMON" CORROSION MONITOR INCLUDING ESTIMATES OF EXPECTED LIFE

CIRCUIT NO.	LINE SECTION	REGION	CONDUCTOR SIZE	AGE (YRS)	CORMON RATING	EXPECTED LIFE (YRS)*
K7B	NT60X63	CENTRAL	500 acsr (54/7)	67	4	67
HL3	NT92X48	CENTRAL	605 acsr (54/7)	59	3	68
K7B	NT63X58	CENTRAL	500 acsr (54/7)	67	4	67
D8S	NW58X9	CENTRAL	266.8, 336.4, 312, 266.8, 477 all acsr	79	4	79
B3	NW39X2-02	CENTRAL	500, 605 (30/7, 54/7)	67	4	67
C3L	NAH9X34-02	CENTRAL	795 acsr (26/7), 1843.2 acsr (72/7)	78	3	88
K1W	NT85X35	CENTRAL	605 acsr (54/7)	49	3	55
H6LC	NT57X51	CENTRAL	795 (26/7)	30	2	42
D10H	NW83X28	CENTRAL	3/0 acsr (6/1), 477 acsr (26/7)	32	4	32
P3S	Q52X65-02	CENTRAL	477 acsr (26/7)	61	4	61
L13W	NT83X31	CENTRAL	605 acsr (54/7)	40	4	40
L14W	NT34X36	CENTRAL	605 acsr (54/7)]	61	4	61
D9H	NT53X17	CENTRAL	605 acsr (54/7), 795 acsr (26/7)	16	2	25
L9C	NT34X66-01	CENTRAL	605 acsr (54/7)	61	3	69
H5E	NT51X36	CENTRAL	795 acsr (26/7)	30	2	42
L13W	NT66X31	CENTRAL	605 (54/7)	61	3	69
B12	NW2X12	CENTRAL	336.4 acsr (30/7)	79	4	79
L14W	NT34X64	CENTRAL	605 acsr (54/7), 795 acsr (26/7)	33	1	63
K7B	NT52X60	CENTRAL	500 acsr (54/7)	67	4	67
D10H	NW28XG36	CENTRAL	3/0 acsr (6/1)	59	4	59
Q7PG	NF50X89	WESTEF	605 acsr (54/7)	64	4	64
Q3L	NF50X62	WESTERN	556.5 al, then 605 acsr (54/7)	67	4	67
T2N	NF90X121-01	WESTERN	345 al & 336.4 acsr (26/7)	49	1	90
K6Z	NW30X53	WESTERN	266.8 acsr (26/7)	21	1	43
P7A	NF89X49-01	WESTERN	605 acsr (54/7)	56	4	56
D9H	NF18X53	WESTERN	605 (54/7) 1192.5 & 795 acsr	67	3	77
Q1N	NF72X47	WESTERN	500 & 605 acsr (54/7)	60	4	60
D9H	NF69X18	WESTERN	605 acsr (54/7)	67	3	77
W7W	NW38X19	WESTERN	336.4(30/7) & 605(54/7) acsr	79	4	79
Z1E	NW55X15-02	WESTERN	477 acsr (26/7)	49	2	65
Z7E	NW56X55-02	WESTERN	266.8(6/7), 477(tap), 795 acsr(26/7)	21	1	43
D10S	NF4X69	WESTERN	605 acsr (54/7)	67	3	77
K6Z	NW14X30	WESTERN	266.8 acsr (26.7), 336.4 al	12	1	30
Q8TG	NF84X44-02	WESTERN	477 acsr (26/7)	64	4	64
K6Z	NW53X3	WESTERN	336.4 kcmil (1977)(26/7)	12	1	30
B2W	NW12X10	WESTERN	336.4 acsr (30/7)	79	4	79
A6C	NF73X74-01	WESTERN	605(54/7), 795(26/7), 1192.5-all acsr	59	4	59
Q2A	NF50X60	WESTERN	605 acsr (54/7)	66	4	66
Q4C	NA1X90	EASTERN	795 kcmil	59	3	65
C7BM	NQL1X24	EASTERN	477 kcmil	49	2	68
C7BM	NQL1XNAB6	EASTERN	477 kcmil	61	2	86
F10MV	Q61X97	EASTERN		61	4	61
F10MV	Q73X24	EASTERN	477 kcmil	61	3	69
C7BM	Q53XNQL1	EASTERN	477 acsr (26/7)	49	2	65
H9A	Q79X55	EASTERN	795 kcmil	56	2	81
B23C	NA47XL7	EASTERN	795 acsr (26/7), 1277.5 acsr (42/7)	48	1	90
L1MB	Q21X71	EASTERN	4/0 acsr	55	3	63
C25H	NA2X57	EASTERN	795 acsr (54/7)	61	3	69
M29C	NAB6XL7	EASTERN	795 kcmil	57	1	100
L1MB	Q21X56	EASTERN	4/0 acsr	55	4	55
P33C	NA90X2	EASTERN	795 acsr (26/7) (54/19)	61	3	69
L1MB	QB6X56	EASTERN	4/0 acsr	55	4	55
S1K	Q39X3	EASTERN	477 (26/7)	61	4	61

* To reach a Cormon rating of 4

TABLE 1 (cont.)

TESTS OF 77 CONDUCTORS USING THE "CORMON" CORROSION MONITOR
INCLUDING ESTIMATES OF EXPECTED LIFE

CIRCUIT NO.	LINE SECTION	REGION	CONDUCTOR SIZE	AGE (YRS)	CORMON RATING	EXPECTED LIFE (YRS)*
W6MC	Q70XQ81	EASTERN	4/0 acsr	31	2	44
H27H	NA10X57	EASTERN	1277.5 acsr (42/7), 795 acsr (54/7)	60	3	67
W6MC	Q70X28	EASTERN	477 kcmil	36	2	50
C7BM	Q53XQ61	EASTERN	336.4 kcmil	47	2	65
W6MC	NQL3XQ58	EASTERN	477 kcmil	36	2	50
M29C	NAL20XL7	EASTERN	795 kcmil	57	1	100
W6MC	NQL3XQ70	EASTERN	477 kcmil	61	3	69
Q3K	Q3X63	EASTERN	477 acsr (26/7)	49	1	90
W6MC	Q61X58	EASTERN	477 kcmil	36	1	70
C28C	NA2XL7-01	EASTERN	795 acsr (54/7) & (26/7)	58	3	66
W6MC	Q10X61	EASTERN	795 kcmil	36	1	70
S4B	Q2X4	EASTERN	4/0 acsr (6/1)	61	4	61
C25H	NA2X57	EASTERN	795 kcmil	61	3	69
C7BM	Q53XNQL1	EASTERN	477 kcmil	49	1	52
C27P	NA2X20	EASTERN	795 kcmil	58	2	82
H23B	NA10X47	EASTERN	795 acsr (26/7)	48	1	90
C28C	NA2XL7	EASTERN	795 kcmil	58	3	65
C7BM	Q61XQ14	EASTERN	336.4 kcmil	62	2	87
C7BM	Q61X14	EASTERN	336.4 (26/7) 795 (26/7)	52	2	74
P3S	Q12X65	EASTERN	477 acsr (26/7)	61	2	86
H24C	NA57XL7	EASTERN	795 kcmil	60	3	68
L1S	FS39X1	N.EAST.	4/0 acsr (6/1)	52	4	52
A7L	P57X12	N.WEST.	6/0acsr, 4/0cop, 477, 336.4 acsr	65	2	90
A6P	P57X2	N.WEST.	477 acsr (26/7)4/0 acsr (6/1)	69	4	67

* To reach a Cormon rating of 4

TABLE 2

TENSILE TESTS OF 50 CONDUCTOR SAMPLES INCLUDING ESTIMATES OF EXPECTED LIFE

CIRCUIT NO.	LINE SECTION	REGION	CONDUCTOR SIZE	AGE (YRS)	%STR.* LOSS	EXPECTED** LIFE (YRS)
20M5	QC20X2036	CENTRAL	4/0	17	22	31
D9G	NW5X51	CENTRAL	336.4 (30/7)	47	50	32
D10H	NW28X36	CENTRAL	6/1	59	17	82
D7G	NW51X67	CENTRAL	266.8 acsr (6/7)	79	62	54
B12	NT76X39	CENTRAL	336.4 30/7	48	13	85
B12/13	NW39X2	CENTRAL	336.4 30/7	48	17	74
D7G	NW5X51	CENTRAL	266.8 & 312 acsr	47	63	25
IDLE	NT60X13	CENTRAL	312 kcmil	78	23	94
W12W	NW10X19	CENTRAL	336.4 kcmil 30/7	79	44	70
B5G	NW55X5	CENTRAL	336.4 acsr(30/7)605 acsr(54/7)	79	15	>100
K7B	NT38X58	CENTRAL	500 kcmil (54/19)	41	2	>100
H4A	QC14X47/QC47X69	CENTRAL	4/0 6/7	69	45	58
E1W	G88X93	G.BAY	477 26/7	35	3	>100
E1R	GB10X9	G.BAY	345 kcmil 19 strands al.	48	14	78
27M2	NW2734X76	WESTERN	3/0 kcmil 7 al. strands	65	24	78
A8W/A11T	NW70X84	WESTERN	605 54/7	60	9	>100
Q8TG	NF50X89	WESTERN	605 54/7	64	8	>100
B12	NW12X76	WESTERN	336.4 30/7	79	42	68
K6Z	NW30X53	WESTERN	266.8 acsr (26/7)	21	12	57
W7W	NW38X19	WESTERN	336.4(30/7) & 605(54/7) acsr	79	50	64
A8W	NW19X11	WESTERN	266.8 6/7	79	14	>100
E1C	FP1X21	WESTERN	3/0 6/1	50	10	36
C2P	NF88X43	WESTERN	336.4 30/7	64	35	61
Q2A	NF50X60	WESTERN	605 54/7	66	20	84
B2W/B8W	NW12X10	WESTERN	336.4 30/7	79	45	66
H2AR	Q77X42	EASTERN	477 acsr (26/7)	49	12	83
M31A	NA84XB6-01	EASTERN	795 acsr (26/7)	57	16	83
Q3M6	Q3X3010	EASTERN	12/7	49	7	95
S1K	Q96X39	EASTERN	477 acsr (26/7)	61	24	71
49M6	QL56X601	EASTERN	336.4 30/7	39	12	79
D4Z	FT66X95	N. EAST	4/0 kcmil 6/7 acsr	34	26	40
T2R	FA25X70	N. EAST	336.4 acsr (30.7)	58	12	>100
S2B	FS26X70	N. EAST	477 26/7	39	12	78
C2T	FA50X19	N. EAST	336.4 30/7	59	11	>100
T2R	FA70X20	N. EAST	4/0 6/1	54	20	73
56M1	P33X18	N. WEST	4/0 acsr (6/1)	52	30	53
C3A	P4X54-02	N. WEST	336.4 kcmil, 30/7 acsr	59	15	98
M1F	FR31X22	N. WEST	336.0 26/7 acsr	31	20	49
C2A	P1X54-02	N. WEST	336.4 kcmil, 30/7 acsr	59	12	>100
SK1	FP50X51	N. WEST	266.8 kcmil 6/7	53	4	>100
56M1	P56X33	N. WEST	4/0 acsr (6/1)	68	37	62
P5M	FR 66X11	N. WEST	312 30/7	46	25	55
P5M	P2X66	N. WEST	312 acsr (30/7)	46	21	61
		N. WEST	336.4 kcmil, 30/7 acsr	79	45	68
			336.4 kcmil, 26/7 acsr	NEW	4	
			336.4 kcmil, 18/1 acsr	NEW	2	
			477 kcmil, 26/7 acsr	NEW	6	
			4/0 kcmil, 6/1 acsr	NEW	3	
			336.6 kcmil, 19 strand	NEW	3	
			795 kcmil, 26/7 acsr	NEW	7	

* From 112 % RTS
** To reach a tensile strength of 80% RTS

TABLE 3

TORSIONAL DUCTILITY TESTS OF 46 CONDUCTOR SAMPLES INCLUDING ESTIMATES OF EXPECTED LIFE

CIRCUIT NO.	LINE SECTION	REGION	CONDUCTOR SIZE	AGE (YRS)	# of TURNS*	EXPECTED** LIFE(YRS)
D9G	NW5X51	CENTRAL	336.4 (30/7)	47	4	45
D10H	NW28X36	CENTRAL	6/1	59	16	74
D7G	NW51X67	CENTRAL	266.8 acsr (6/7)	79	2	74
B12	NT76X39	CENTRAL	336.4 30/7	48	23	75
B12/13	NW39X?	CENTRAL	336.4 30/7	48	9	53
D7G	NW5X51	CENTRAL	266.8 & 312 acsr	47	11	53
IDLE	NT60X13	CENTRAL	312 kcmil	78	2	74
W12W	NW10X19	CENTRAL	336.4 kcmil 30/7	79	12	87
B5G	NW55X5	CENTRAL	336.4 acsr(30/7)605 acsr(54/7)	79	8	82
K7B	NT38X58	CENTRAL	500 kcmil (54/19)	41	6	42
H4A	QC14X47/QC47X69	CENTRAL	4/0 6/7	69	2	66
E1W	G88X98	G.BAY	477 26/7	35	26	70
A8W/A11T	NW70X84	WESTERN	605 54/7	60	16	76
Q8TG	NF50X89	WESTERN	605 54/7	64	17	80
B12	NW12X76	WESTERN	336.4 30/7	79	4	78
K6Z	NW30X53	WESTERN	266.8 acsr (26/7)	31	29	63
W?W	NW38X19	WESTERN	336.4(30/7) & 605(54/7) acsr	79	10	85
A8W	NW19X11	WESTERN	266.8 6/7	79	4	77
E1C	FP1X21	WESTERN	3/0 6/1	50	4	49
C2P	NF88X43	WESTERN	336.4 30/7	64	3	62
Q2A	NF50X60	WESTERN	605 54/7	66	4	64
B2W/B8W	NW12X10	WESTERN	336.4 30/7	79	3	75
H2AR	Q77X42	EASTERN	477 acsr (26/7)	49	34	120
M31A	NA84XB6-01	EASTERN	795 acsr (26/7)	57	18	75
Q3M6	Q3X3010	EASTERN	12/7	49	7	51
S1K	Q96X39	EASTERN	477 acsr (26/7)	61	16	76
49M6	QL56X601	EASTERN	336.4 30/7	39	25	70
D4Z	FT66X95	N. EAST	4/0 kcmil 6/7 acsr	34	2	24
T2R	FA25X70	N. EAST	336.4 acsr (30.7)	58	7	60
S2B	FS26X70	N. EAST	477 26/7	39	27	77
C2T	FA50X19	N. EAST	336.4 30/7	59	10	64
T2R	FA70X20	N. EAST	4/0 6/1	54	10	60
56M1	P33X18	N. WEST	4/0 acsr (6/1)	52	4	50
C3A	P4X54-02	N. WEST	336.4 kcmil, 30/7 acsr	59	13	68
		N. WEST	336.4 kcmil, 30/7 acsr	79	3	75
M1F	FR31X22	N. WEST	336.0 26/7 acsr	31	40	150
C2A	P1X54-02	N. WEST	336.4 kcmil, 30/7 acsr	59	20	78
SK1	FP50X51	N. WEST	266.8 kcmil 6/7	53	15	65
56M1	P56X33	N. WEST	4/0 acsr (6/1)	68	2	63
P5M	FR 66X11	N. WEST	312 30/7	46	1	41
P5M	P2X66	N. WEST	312 acsr (30/7)	46	2	43
			336.4 kcmil, 26/7 acsr	NEW	36	
			336.4 kcmil, 18/1 acsr	NEW	38	
			477 kcmil, 26/7 acsr	NEW	36	
			4/0 kcmil, 6/1 acsr	NEW	30	
			795 kcmil, 26/7 acsr	NEW	34	

* Average of outer steel strands
** To reach a ductility of 5 turns

TABLE 4

CONDUCTOR CONDITION ACROSS THE PROVINCE SORTED BY REGIONS AND NUMBER OF LAYERS OF STEEL

	COMMON					TENSILE TESTS					DUCTILITY TESTS					OVERALL
	# OF DATA	AVG AGE	AVG. CORE GALV LOSS	AVG. USEFUL LIFE	90% CONF	# OF DATA	AVG AGE	% LOSS OF TENSILE STRNGTH	AVG. USEFUL LIFE	90% CONF	# OF DATA	AVG AGE	# OF TURNS TO FAIL.	AVG. USEFUL LIFE	90% CONF	AVG. USEFUL LIFE
CENTRAL & GB+ REGIONS	20	55	3.3	60	6.2	14	55	18.	75	16.1	12	59	10	66	6.7	67
WESTERN REGION	18	53	2.9	63	6.6	11	64	22.	84	12.6	10	64	9.3	70	5.8	72
EASTERN REGION	36	53	2.4	70	3.9	5	51	12.6	82	7.6	5	51	20	78	21.	77
NORTHERN** REGIONS	3	62	3.3	70	27.0	11	56	17.6	85	14.2	11	56	13.3	73	13.6	76
1-LAYER CONDUCTORS	9*	54	3.7	56	5.7	11	58	28.	67	7.8	9	62	5.9	65	6.	63
2-LAYER CONDUCTORS	65*	55	2.7	66	4.	30	57	18.	86	6.8	29	57	14.	73	6.	75
PROVINCE	77	54	2.8	66	3.	41	57	20.	81	7.	38	58	12	71	6.	73

+ Georgian Bay
* From 77 test results, 3 did not contain enough information regarding the conductor structure
** Northeastern and Northwestern regions combined

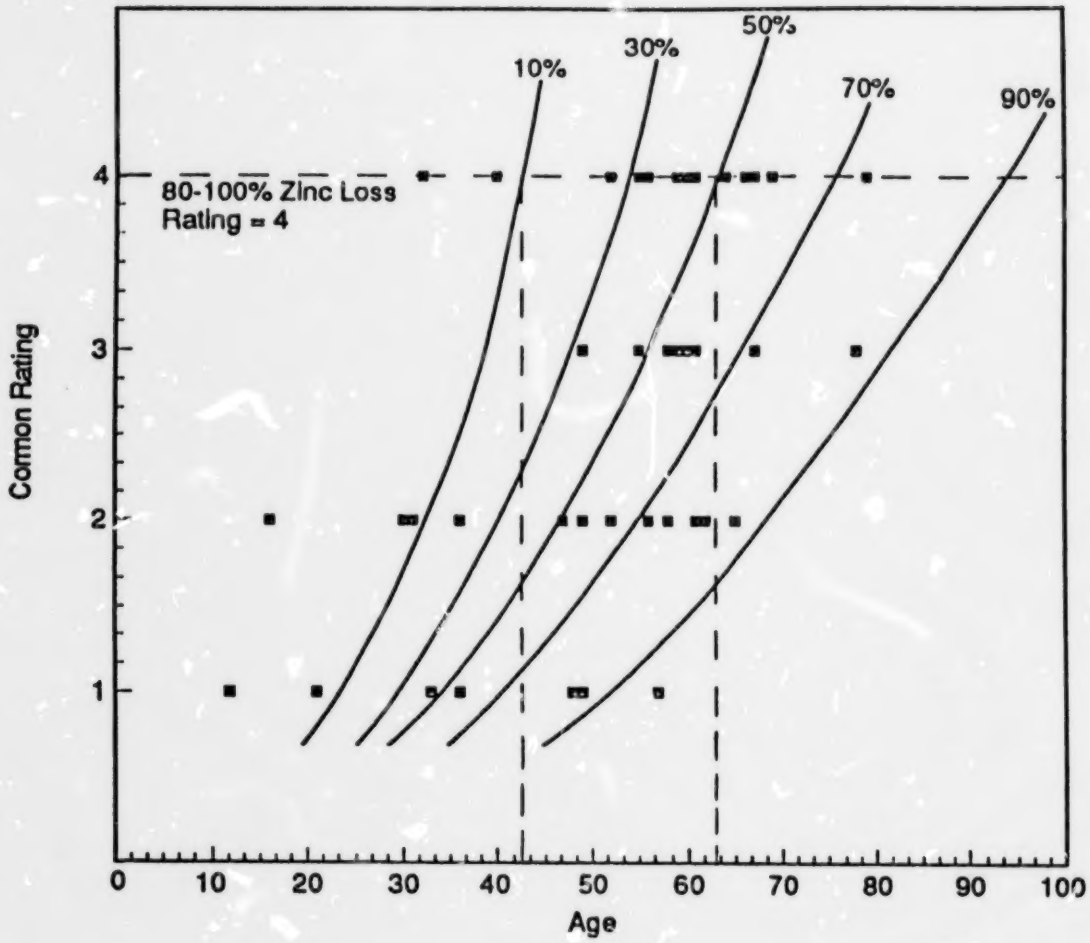

FIGURE 1

CORMON RATING VS AGE FOR 77 CONDUCTOR SAMPLES
Average Life 63 Years
Lower Decile 43 Years
Mean Curve $y = 0.00049\ x^{2.17}$

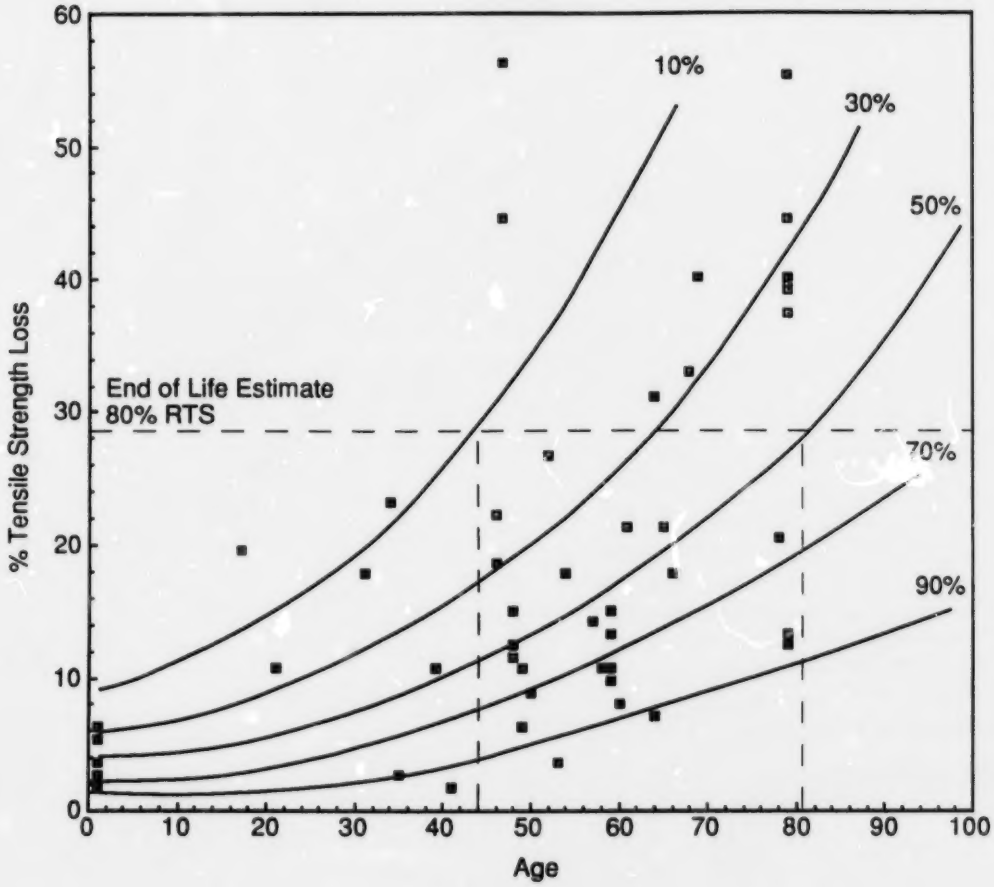

FIGURE 2

TENSILE STRENGTH LOSS VS AGE FOR 50 CONDUCTOR SAMPLES BASED ON AN AVERAGE INITIAL STRENGTH OF 112% RTS

Average Life to 80% RTS = 81 Years
Lower Decile Life to 80% RTS = 44 Years
Mean Curve $y = e^{1.41 + 0.024\,x}$

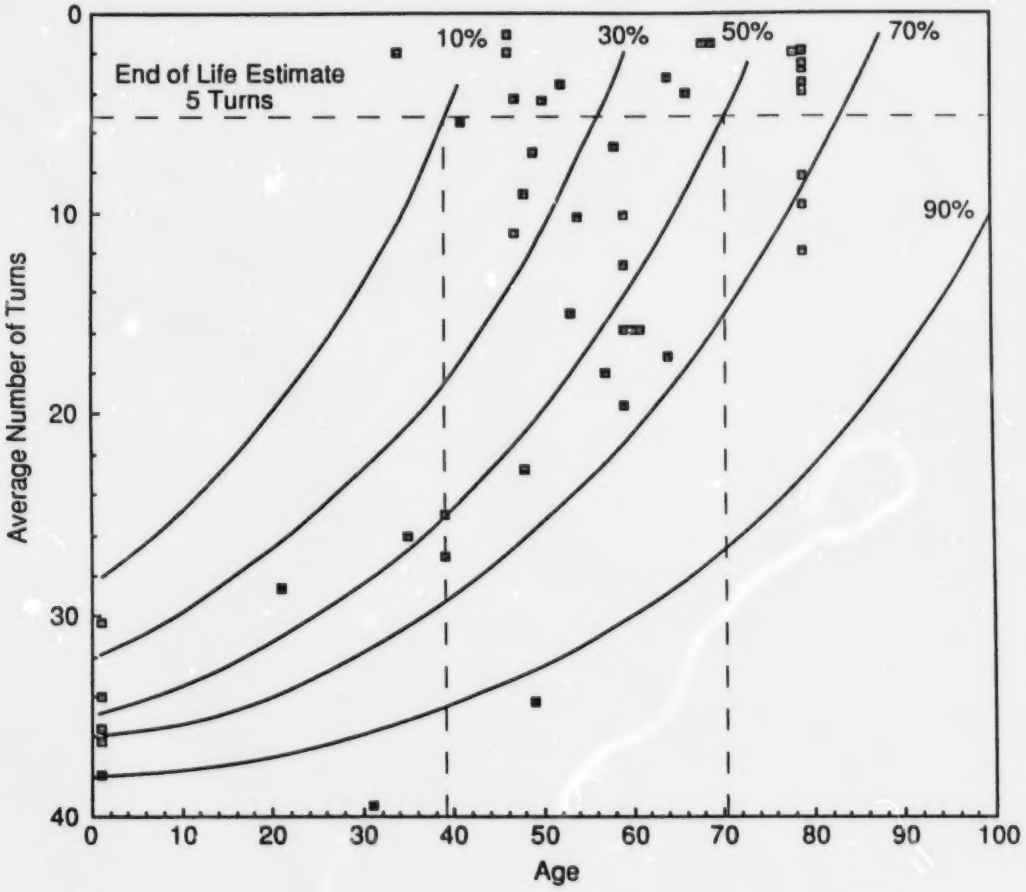

FIGURE 3

TORSIONAL DUCTILITY OF OUTER LAYER OF STEEL CORE VS AGE FOR 46 CONDUCTOR SAMPLES
Average Life to 5 Turns =71 Years
Lower Decile to 5 Turns =39 Years
Mean Curve = 40 - $e^{1.65 + 0.027 x}$

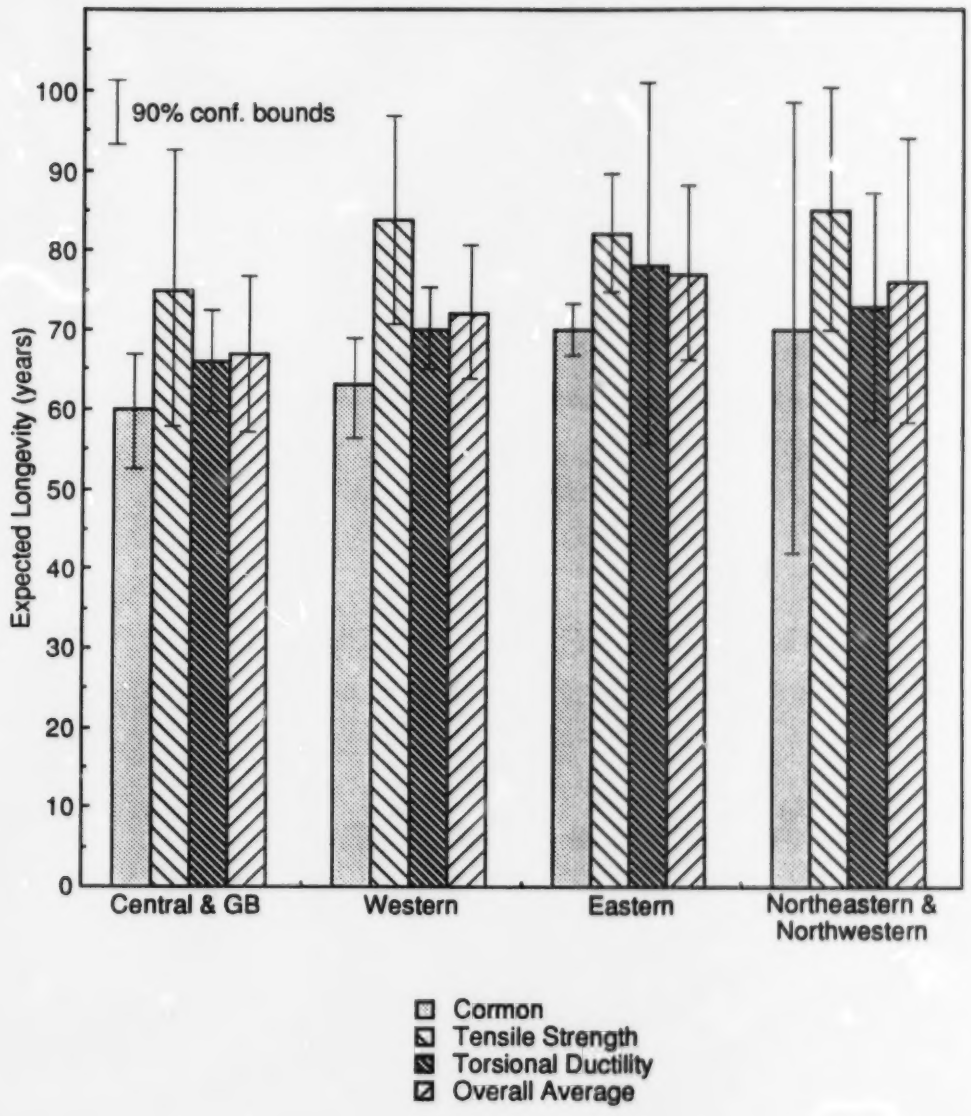

FIGURE 4

REGIONAL AVERAGES OF TEST RESULTS

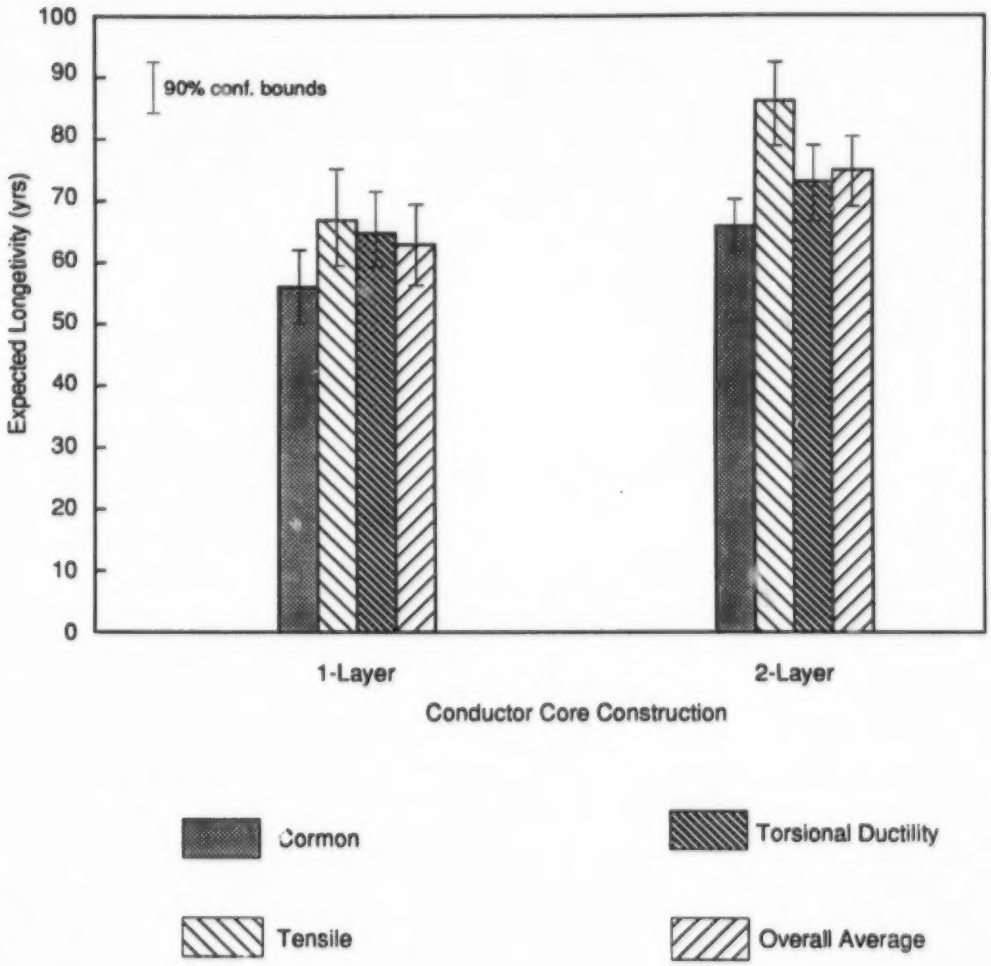

FIGURE 5

TEST RESULTS CATEGORIZED ACCORDING TO CONDUCTOR CORE CONSTRUCTION

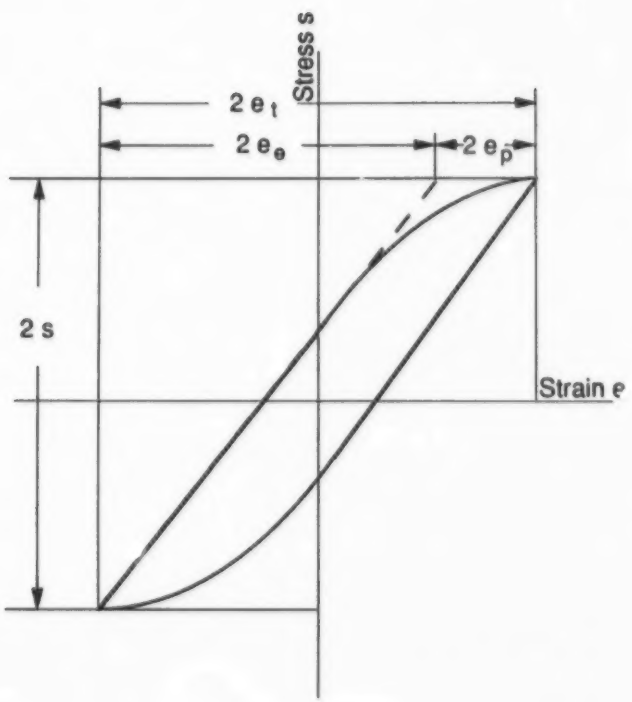

FIGURE 6

TOTAL STRAIN, e_t, PLASTIC STRAIN, e_p, AND ELASTIC STRAIN, e_e AS A FUNCTION OF STRESS, s, DURING CYCLIC LOADING OF STEEL IN THE PLASTIC REGIME

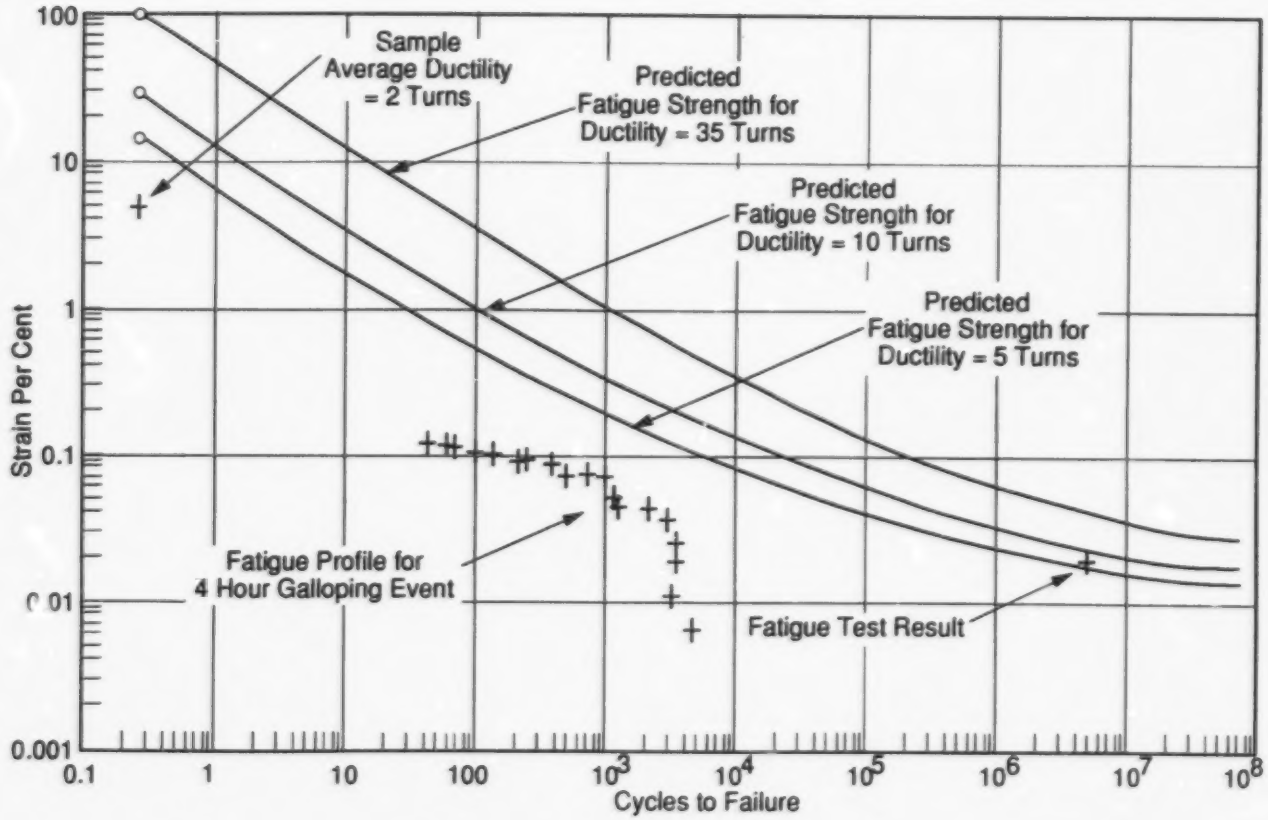

FIGURE 7

FATIGUE CURVE FOR STEEL SAMPLES BASED ON TORSIONAL DUCTILITY TESTS INCLUDING STRAIN HISTORY FROM A REPRESENTATIVE GALLOPING EVENT

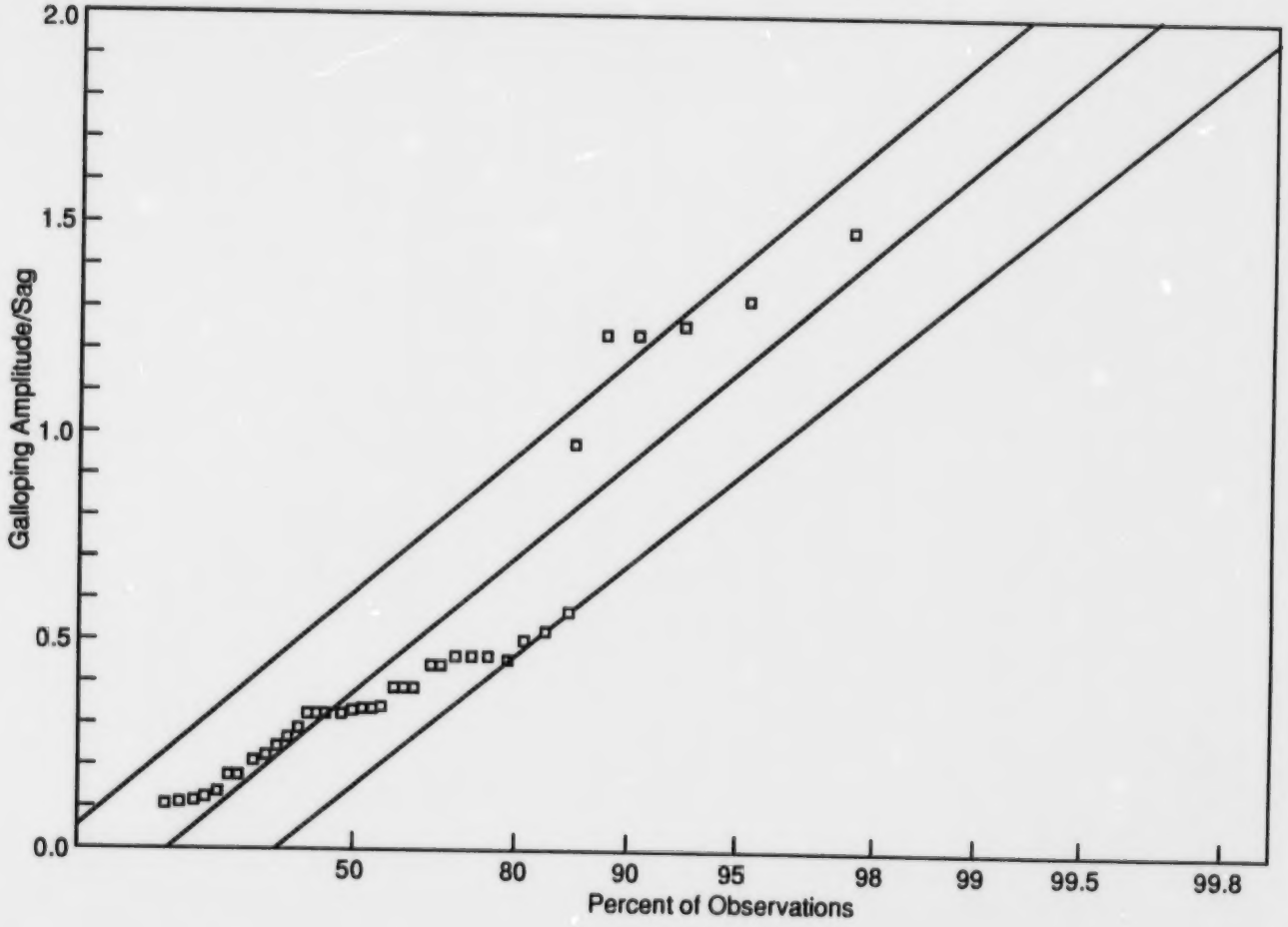

FIGURE 8

COMPILATION OF GALLOPING AMPLITUDE DATA BASED ON 47 OBSERVATIONS ON SINGLE CONDUCTORS